IV. EMISSIONS AND AIR POLLUTANT TRANSPORT

A. PURPOSE

Ambient and visual air quality degradation and acidic deposition in Shenandoah National Park (SHEN) are the result of distant and local (including in-park) pollutant emissions. Based upon pollutant transformations and lifetimes in the atmosphere and on regional climatology, the various emissions sources contribute in varying degree to pollutant loading or exposure in the park. The purpose of this section is to summarize regional and local emissions and assess the effects of atmospheric transport processes. Major air pollution source regions and states affecting the park are identified. Several scenarios of future emissions controls are described, providing the foundation for evaluation of possible resource recovery in the future.

B. RECENT AND PROJECTED FUTURE REGIONAL EMISSIONS

The emissions from two base years, 1990 and 1996, are analyzed in this assessment. Four estimates of future emissions were developed and analyzed as well. These future emissions scenarios were developed by applying growth and emissions control assumptions to the 1996 base year inventory. The development of these emission inventories is discussed here.

State-level sulfur (S) and nitrogen (N) 1990 emissions data were compiled for this project from the annual National Emissions Trend inventory, as revised in October 2000 by the U.S. Environmental Protection Agency (EPA). The area source emissions were taken from version 3.01a, the mobile source emissions from version 3.00, and the point source emissions from version 2.00. In all cases, mobile (e.g., on-highway cars, light trucks and heavy trucks), area-stationary (e.g., commercial and residential heating and vented emissions from commercial buildings), and area-nonroad (off-road vehicles, tractors, construction equipment, locomotives, and ships) emissions were developed at the county level, whereas point source locations were defined in terms of their latitude and longitude.

In addition, 1996 emissions data were derived from the annual National Emissions Trend inventory (U.S. EPA 2000a). The point source emissions for electricity generating units (EGUs) and non-EGUs were taken from version 3.12, and the stationary area-source emissions from version 3.11. Other 1996 emissions were developed by EPA as part of their regulatory analysis of heavy-duty engine and vehicle standards and highway diesel fuel rulemaking. The majority of the mobile nonroad source emissions were developed using EPA's draft NONROAD model, while aircraft, commercial marine, and locomotives (not in NONROAD) were estimated separately (U.S. EPA 2000b). The combined categories of all nonroad emissions are termed here area-nonroad emissions. For 1996 mobile source emissions, the on-highway vehicle emission

inventory created in 1998 was updated. In particular, a new vehicle miles traveled (VMT) mapping from the Highway Performance Monitoring System data to MOBILE5b was developed by EPA and the latest information on 1996 control programs was used, including Inspection and Maintenance programs, Reformulated Gasoline use, Oxygenated Gasoline use, and the Low Emission Vehicle program. Details are provided in U.S. EPA (2000b). The 1996 Case reflects 1990 Clean Air Act Amendments (CAAA) Title IV Phase I implementation of EGU sulfur dioxide (SO_2) and nitrogen oxide (NO_x) emission reductions.

The airsheds of SHEN contain numerous major stationary sources of air pollution. Emissions from mobile sources and many stationary sources are expected to increase with substantial population and industrial growth in Virginia and other airshed states (Shenandoah National Park 1998b). More Prevention of Significant Deterioration (PSD) air permit applications have been reviewed by the National Park Service (NPS) Air Resources Division (ARD) for SHEN than for any other NPS area (Figure IV-1). In addition, SHEN and Great Smoky Mountains National Park are two Class I parks where the NPS has been able to compile an overwhelming amount of data indicating that resources are damaged by human-caused air pollution (NPS 1990, NPS 2000c).

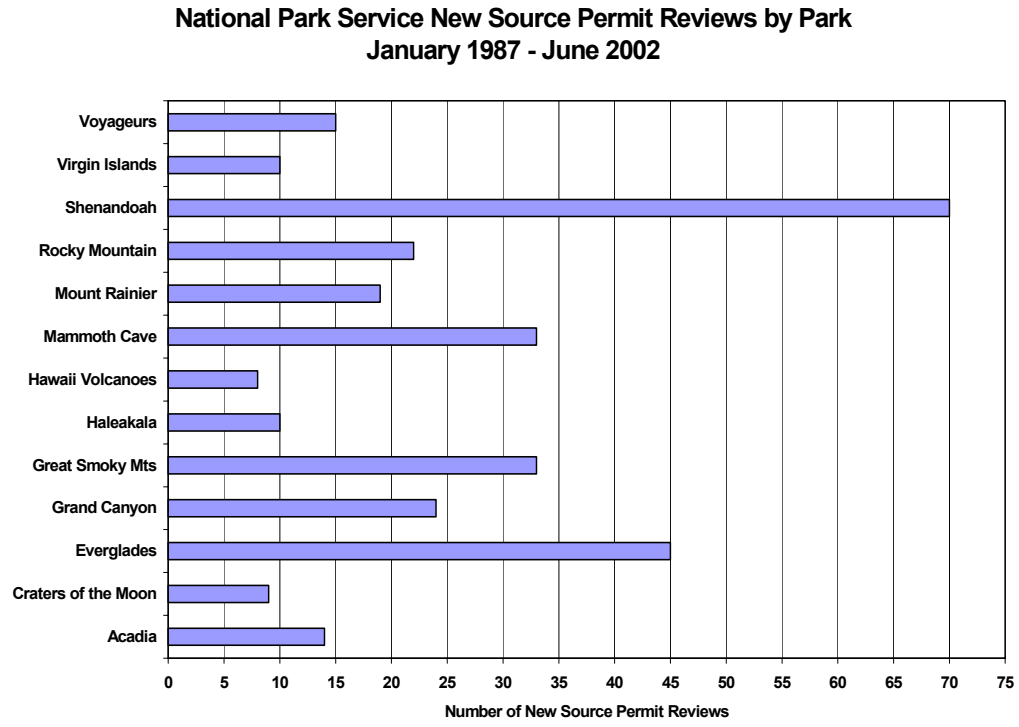

Figure IV-1. New source permit reviews during the period January 1987 to June 2002. In addition, there have been about 6 additional Virginia/ Shenandoah new source permit reviews since June 2002.

A brief description is given here of the four future emissions scenarios selected for this assessment. State-level emissions for fifteen states surrounding SHEN are listed in Tables IV-1 and IV-2 for the 1990 Base Case, the 1996 case, and the four scenarios for future SO_2 and NO_x emissions, respectively. The top four states for both SO_2 and NO_x Base Case emissions were Ohio, Indiana, Pennsylvania, and Illinois. Each of the scenarios is described below.

Scenario 1. 2007/2010 Base with NO_x State Implementation Plan (SIP) Call

Scenario 1 provides our best estimate of emissions expected for the 2010 time frame. This scenario represents the base 1990 CAAA effect on emissions due to control programs already in place, with projections provided to 2010. Scenario 1 consists of projected emissions for all source categories assuming a reasonable amount of economic growth as projected by the Bureau of Economic Analysis (BEA) in the Department of Labor, and emissions limitations due to existing 1990 CAAA air pollution emissions control programs that have been codified in law, with rules promulgated and any litigation settled as of summer 2000[1]. The emissions limitations

Table IV-1. State-level annual emissions totals of SO_2 for the 1990 Base Case, the 1996 case, and the four scenarios (tons/year). The top five states are shaded for each scenario.

	1990 Base	1996	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Delaware	100,000	97,303	86,676	96,403	62,826	52,167
Georgia	1,000,330	594,127	720,507	719,843	204,996	156,647
Illinois	1,261,534	1,070,104	836,073	863,813	543,451	333,329
Indiana	1,920,416	1,116,166	729,283	689,224	397,407	289,683
Kentucky	1,034,272	767,112	570,764	512,412	232,278	210,750
Maryland	435,774	298,151	257,244	233,549	73,650	70,394
Michigan	726,298	572,744	565,822	536,399	300,129	250,124
New York	867,415	627,866	522,022	405,096	359,902	234,217
North Carolina	487,616	577,874	693,293	663,277	250,218	191,850
Ohio	2,736,237	1,974,126	1,380,563	1,224,841	577,144	401,665
Pennsylvania	1,517,739	1,291,592	886,909	866,065	333,294	250,912
South Carolina	292,567	285,982	285,136	297,850	143,150	107,738
Tennessee	1,077,345	753,602	505,268	425,899	265,951	167,749
Virginia	403,610	341,015	353,543	347,235	232,967	170,651
West Virginia	1,074,715	773,282	606,655	530,000	196,623	164,911

[1] This implies the NO_x SIP call in the eastern states is based upon implementation of a one hour standard and does not take into account the final decision handed down by the DC Circuit Court March 26, 2002.

Table IV-2. State-level annual emissions totals of NO_x for the 1990 Base Case, the 1996 case, and the four scenarios (tons/year). The top five states are shaded for each scenario.

	1990 Base	1996	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Delaware	102,989	84,705	65,833	51,747	44,038	36,379
Georgia	687,001	756,961	675,430	531,896	370,390	298,698
Illinois	922,261	1,135,766	836,627	671,787	565,381	441,999
Indiana	905,979	881,712	598,377	456,076	328,825	276,648
Kentucky	674,772	752,302	510,432	425,022	295,271	260,610
Maryland	354,842	354,692	240,890	180,155	143,809	126,394
Michigan	887,552	904,068	708,591	579,000	511,067	394,655
New York	844,656	765,350	523,248	346,138	324,112	276,303
North Carolina	577,599	732,552	523,519	402,401	319,437	257,449
Ohio	1,156,094	1,310,664	793,495	614,480	479,899	396,716
Pennsylvania	1,081,534	1,086,095	847,346	661,327	542,779	397,475
South Carolina	353,655	401,430	298,566	232,078	193,871	146,594
Tennessee	727,134	816,578	557,305	420,384	357,456	285,032
Virginia	564,357	609,972	456,249	331,008	296,699	239,502
West Virginia	568,976	514,532	366,492	308,767	201,437	159,869

expected from existing programs currently "on the books" as of the year 2000 include Federal, state and local emissions control programs. The major programs included in this base emissions projection are the Federal CAAA Title IV limits on electricity generation for SO_2 and NO_x, designed to address the problem of acid deposition; Federal Tier II vehicle standards, designed to help alleviate problems related to urban smog; the Federal NO_x SIP Call in approximately twenty states located east of the Mississippi River, designed to address tropospheric O_3 attainment problems under the Federal National Ambient Air Quality Standards (NAAQS); and the Federal Heavy Duty Diesel Vehicle (HDDV) Standards program. Details regarding the future year projections are specified in the technical support document for the HDDV rule (U.S. EPA 2000b). The two programs accounting for the great majority of the emissions reductions by 2010 are the Title IV limits and the Federal NO_x SIP Call. Scenario 1 was constructed by using the 2007 HDDV inventory for point, area, and mobile source emissions, and a 2010 Integrated Planning Model (IPM) projection for electricity generation emissions as revised to reflect the result of litigation decisions finalized in the summer of 2000.

Scenario 2. 2020 CAAA with Tier II and Heavy Duty Diesel Regulations

Scenario 2 provides the current best estimate of emissions expected for the 2020 time frame due to CAA regulations that are now in place. This scenario has the same basic set of control programs as described above, but with their effects on emissions now projected to the year 2020. The reduction in mobile source emissions due to the new Tier II Vehicle Standards is becoming more evident due to great penetration of the control technology over time into the fleet of vehicles actually on the road. It typically takes 15 years for the effect of new mobile source emissions reductions to be fully actualized. In addition, the HDDV standards have been implemented and are resulting in noticeable improvements in emissions from heavy duty diesels. Finally, CAAA Title IV acid rain controls on EGUs are being seen near the level of the cap, having nearly exhausted the banked allowances from reductions beyond required amounts in earlier years. The Tier II and HDDV standards are responsible for a large majority of the emissions reductions between 2010 and 2020, i.e., differences between Scenario 1 and Scenario 2.

Scenario 3. 2020 CAAA with the Addition of Stringent Utility Controls

The objective of Scenario 3 is to assess the potential for ambient and visual air quality and acidic deposition improvements beyond current plans if additional, maximally-feasible controls were applied to EGUs only. This scenario, and Scenario 4 (described below) were devised because current plans are not expected to produce air quality and acidic deposition levels low enough to be considered protective of all sensitive receptors (e.g., visibility, acid-sensitive streams and biota, O_3-sensitive plants). This scenario takes the projected emissions levels in 2020 for all sectors as identified above and adds additional controls to EGUs. This case imposes a nationwide 90% reduction in EGU SO_2 emissions beyond Title IV acid rain emission control levels. The controls in this scenario are imposed starting in the year 2005. The existing allowance bank for SO_2 allowances due to excess reductions in earlier years is not discounted[2]. The EGU NO_x emissions are constrained starting in 2005 at an annual national emission rate of 0.10 lb NO_x (as nitrogen dioxide) per million BTU of heat input. This NO_x scenario is a cap and trade scenario operating annually and nationally (in the contiguous 48 States and Washington,

[2] This means that any and all allowances banked in years prior to 2005 as part of CAAA Title IV acid rain program compliance are available in subsequent years. The analysis indicates, however, that the bank is essentially used up by the year 2020.

DC). Any existing banked allowances from excess reductions beyond the required reduction, due to existing NO_x control programs (such as the Ozone Transport Commission and any cap and trade SIP Call programs), are available for use in years 2005 and beyond[3].

Scenario 4. 2020 CAAA with the Addition of Stringent Controls on Utility, Industry-Point, and Mobile Sources

The purpose of Scenario 4 is to assess the levels of air quality and acidic deposition that might be attained through additional, stringent controls of EGU (same as Scenario 3), non-EGU and mobile source emissions. The objective was to determine if air quality levels could be achieved that would be considered protective of the park's visibility and aquatic and terrestrial ecosystems. This scenario incorporates additional reductions from sources other than electricity generation to the limit of currently available commercial reduction technology. These additional reductions are combined with the stringent EGU reductions modeled in Scenario 3. The target level for this analysis of control strategies was to achieve 50% SO_2 and NO_x emissions reductions in 2020 nationwide from point sources other than electricity generation and mobile sources. The baseline for non-EGU point source and mobile source reductions was the suite of emissions projections that were prepared for the HDDV rulemaking. Methods used to prepare the baseline emissions projections used in this analysis are described in Pechan and Associates (2001). Non-utility (non-EGU) sources were analyzed to determine the control technology predicted to be in place in 2020 for the HDDV analysis. Given the base 2020 technologies, estimates were made of the maximum amount of emissions reduction possible, with the technologies that are currently commercially available, that can be applied to the specific sources as listed in the inventory. Complete description of the analysis was provided in Pechan and Associates (2001). Light duty mobile vehicles emissions were adjusted to reflect super-ultra-low emissions vehicles consistent with the California Clean Car alternatives (CARB 2001), thereby achieving additional reductions beyond the Federal or state rules in place in the rest of the country as of the summer of 2000.

Using the definition of each of the four scenarios, future emissions were projected for each scenario. The base emissions inventories for 2007 (Scenario 1) and 2020 (Scenario 2) were developed by applying growth and control assumptions to the 1996 Base Year inventory. The

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[3] It should be noted, however, that the control level is sufficiently stringent that banking of NO_x allowances is not significant and can essentially be considered zero by 2020.

IPM model (U.S. EPA 2002a,b) was used to project unit-level emissions for EGU point sources. New units were incorporated in the simulation where needed to meet projected generation demands. Complete implementation of the 1990 CAAA Title IV limits on electricity generation emissions, set for 2010, were assumed for EGU point sources. For the non-EGU sources and non-mobile emissions, 1995 BEA Gross State Product growth projections (BEA 1995) at the state level were utilized to estimate changes in activity factors and industrial mix from 1996 to 2007 and 2020. For mobile emissions, the number of VMT was projected from 1996 using VMT projection data (at the county, vehicle type, and roadway type level of detail) from EPA's Tier 2 rulemaking (U.S. EPA 1999). Fleet emissions were estimated based on the MOBILE5b emission factor model with some additional adjustments. The growth and control assumptions are documented in U.S. EPA (2000b). For the emissions control scenarios, ammonia (NH_3) emissions were kept constant at the mass emissions rates of the early 1990s. After applying the changes in activity and VMT, together with the effect of existing emissions control programs, to create future Base Cases, additional controls were added to reflect the alternative scenarios for 2020. Estimates of major emissions were developed at the county level for mobile highway, stationary non-road, EGU, non-EGU, and stationary area sources. These mass emissions inventories were developed for winter and summer months for input to the emissions processing models used to create the gridded inputs for the air quality model.

Emissions summaries for 1990, 1996, and the future projections were combined into five source categories for the modeling analysis: Area Stationary, Area Nonroad, Mobile, EGU-Point and non-EGU Point Sources. To provide an overview of the changes in emissions associated with each scenario, Area Stationary, Area Nonroad and Mobile Sources were grouped and termed Surface Sources whereas EGU-Point Sources and non-EGU Point Sources were grouped and termed Point Sources. In addition, the emissions for the top 10 and top 5 states affecting SHEN were summed for the overview. The annual emissions for the top 10 and top 5 states for the two groups are given in Table IV-3 for the 1990 Base Case, the 1996 Case and the 4 future scenarios. Bar charts in Figures IV-2 and IV-3 show the annual SO_2 and NO_x emissions, respectively, from Table IV-3 for the top 10 states. The percent changes from the 1990 Base Case are given in Table IV-4. Major reductions in emissions are anticipated as the result of current rules and regulatory plans, represented by Scenario 2. Under the current set of rules that exist or are being promulgated, nationwide SO_2 emissions would be reduced by 47% from 1990

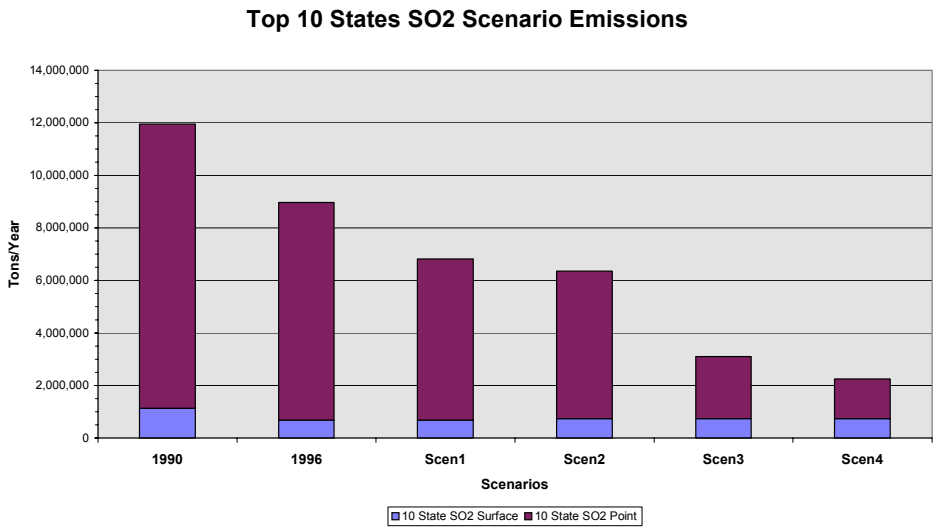


Figure IV-2. Bar chart of SO_2 emissions showing Surface and Point emissions for the top 10 states in 1990, 1996, and each of the scenarios.

Table IV-3. Summary of annual SO_2 and NO_x emissions subdivided into Surface and Point Sources for the 1990 Base, 1996 and the four scenarios.

	1990	1996	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Emissions for Top 10 States Tons/Year (000s)						
SOx - Surface	1,131	684	676	742	742	742
SOx - Point	10,818	8,279	6,143	5,615	2,361	1,510
SOx - Total	11,949	8,963	6,820	6,356	3,103	2,252
NOx - Surface	3,759	4,510	3,416	2,198	2,198	1,952
NOx - Point	3,774	3,685	2,315	2,273	1,333	889
NOx - Total	7,534	8,195	5,731	4,471	3,531	2,842
Emissions for Top 5 States Tons/Year (000s)						
SOx - Surface	569	411	395	423	423	423
SOx - Point	6,198	4,736	3,403	3,058	1,150	776
SOx - Total	6,767	5,147	3,798	3,481	1,572	1,199
NOx - Surface	1,876	2,309	1,727	1,082	1,082	951
NOx - Point	2,073	1,945	1,260	1,236	758	500
NOx - Total	3,949	4,254	2,987	2,318	1,840	1,451
Surface = Area-Stationary + Area-Nonroad + Mobile Point = EGU-Point Sources + non-EGU-Point Sources						

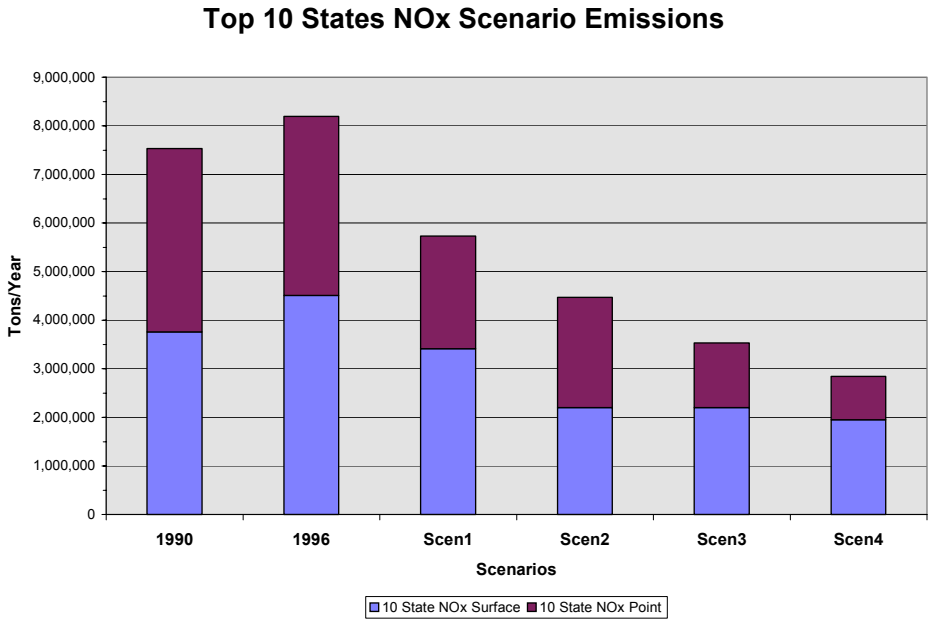


Figure IV-3. Bar chart of NO_x emissions for Surface and Point Source emissions for the top 10 states in 1990, 1996, and each of the scenarios.

Table IV-4. Summary of the percent changes in annual SO_2 and NO_x emissions from the 1990 Base Case to 1996 and the four future scenarios for the Surface and Point Source categories.

	1996	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Percent Change Top 10 States[a]					
SOx - Surface[b]	-39.6%	-40.2%	-34.4%	-34.4%	-34.4%
SOx - Point[c]	-23.5%	-43.2%	-48.1%	-78.2%	-86.0%
SOx - Total	-25.0%	-42.9%	-46.8%	-74.0%	-81.2%
NOx - Surface	20.0%	-9.1%	-41.5%	-41.5%	-48.1%
NOx - Point	-2.4%	-38.7%	-39.8%	-64.7%	-76.4%
NOx - Total	8.8%	-23.9%	-40.7%	-53.1%	-62.3%
Percent Change Top 5 States					
SOx - Surface	-27.8%	-30.6%	-25.7%	-25.7%	-25.7%
SOx - Point	-23.6%	-45.1%	-50.7%	-81.5%	-87.5%
SOx - Total	-23.9%	-43.9%	-48.6%	-76.8%	-82.3%
NOx - Surface	23.1%	-7.9%	-42.3%	-42.3%	-49.3%
NOx - Point	-6.1%	-39.2%	-40.4%	63.4%	-75.9%
NOx - Total	7.7%	-24.4%	-41.3%	-53.4%	-63.3%

[a] To identify which are the Top 5 or the Top 10 states, as emissions sources for SHEN, see Tables IV-1 and IV-2
[b] Surface = Area-Stationary + Area-Nonroad + Mobile
[c] Point = EGU-Point Sources + non-EGU-Point Sources

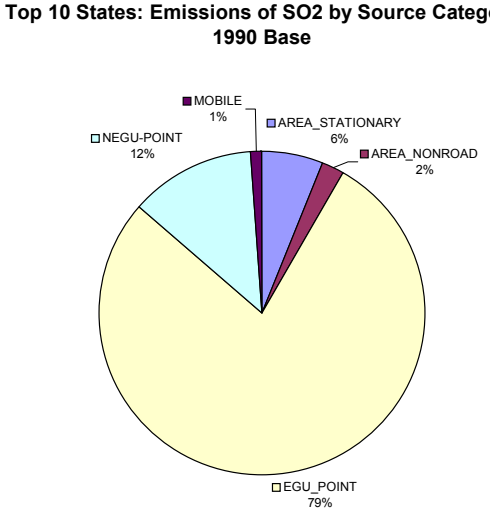
levels and NO_x emissions reduced by 41% relative to 1990. Scenarios 3 and 4 represent significant reductions beyond current plans.

Compared to the levels of emissions anticipated for Scenario 2, Scenario 4 would further reduce nationwide SO_2 emissions by 64%. The largest SO_2 reduction occurs between Scenarios 2 and 3. For nationwide NO_x emissions, the reductions are important but less dramatic; between Scenario 2 and 4 they are 36%. The NO_x reduction from Scenario 2 to 3 is 21% and from Scenario 3 to 4 is 18%. The trend in the magnitude of SO_2 emissions from 1990 over the scenarios is shown in Figure IV-2. There were fairly large reductions in SO_2 emissions from 1990 to 1996 and then from 1996 to Scenario 1 that are the result of the 1990 CAAA Title IV Phase 1 (1996) and Phase 2 (Scenario 1) controls, approximately 3 million and 2 million tons of SO_2, respectively. There is only a small additional reduction of SO_2 emissions with Scenario 2 because SO_2 is not targeted in the emissions controls specified for this scenario. There is more than a 3 million ton reduction of SO_2 between Scenario 2 and 3, a significant additional reduction. An additional 800,000 tons of SO_2 is assumed to be removed in going from Scenario 3 to 4. The vast bulk of the additional SO_2 reductions between 1990 and Scenario 4 come from the EGUs, approximately 9.3 million tons out of the total of 9.7 million tons for the top 10 states.

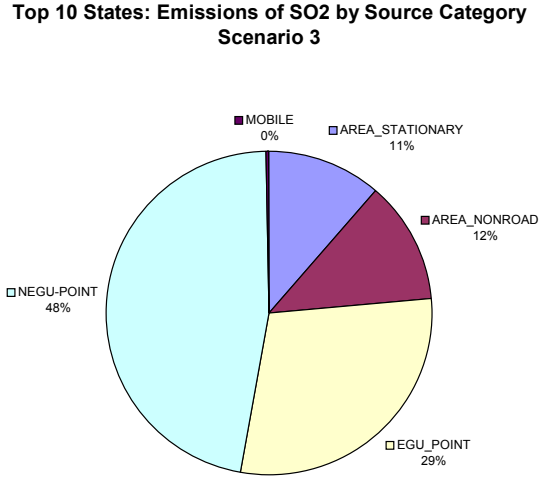
The proportion of emissions in each source category changes dramatically for SO_2 between 1990, Scenario 3, and Scenario 4. This is shown in the pie charts of Figure IV-4 for the top 10 states. In 1990, EGU point sources made up 79% of the SO_2 emissions, while the EGU and non-EGU point sources together made up 91%. After the significant reductions in EGU SO_2 emissions for Scenario 3, their estimated proportion was reduced to 29% and the non-EGU point source proportion expanded to 48%. Together, they still accounted for approximately three-quarters of the SO_2 emissions. With the major non-EGU point reduction in SO_2 emissions for Scenario 4, point sources still accounted for 67% of the SO_2 emissions and the area-stationary and area-nonroad sources quadrupled from 8% in 1990 to 33% in Scenario 4. It took the strong focus on reducing SO_2 point source emissions, 86% reduction for point sources compared to the 34% reduction for surface sources, to achieve this dramatic shift in proportions of SO_2 emissions attributed to each sector.

The trend in the magnitude of NO_x emissions from 1990 over the scenarios is shown in Figure IV-3. There was an increase in NO_x emissions from 1990 to 1996, then continual reductions for each scenario step after 1996. Compared to 1990, the additional increment in the percent reductions becomes progressively smaller, about two thirds as large as the previous

(a)



(b)



(c)

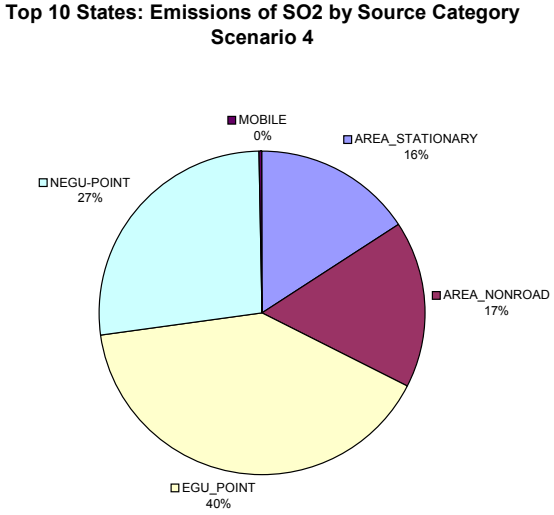


Figure IV-4. Pie chart of SO_2 emissions broken down by five source categories comparing (a) 1990, (b) Scenario 3, and (c) Scenario 4.

scenario increment for each successive scenario percent change (24%, 17%, 13% and 8% for Scenarios 1-4). If each scenario is compared only to the previous one, such as the reduction from Scenario 1 to 2, then the percent reductions are more even, being 23%, 21%, 18% for Scenario 1-to-Scenario 2, Scenario 2-to-Scenario 3, and Scenario 3-to-Scenario 4, respectively. For simulated NO_x emissions reductions, both the surface sources (mobile) and the point sources are important. From 1996 to Scenario 1, surface emissions are reduced by 1.1 million tons. More than half of the 4.7 million ton NO_x emissions reduction between the 1990 Base and Scenario 4 comes from the EGUs. Non-EGU reductions contribute 440,000 tons, increasing the point source contribution to 2.9 million tons. Mobile source reductions are important at 1.8 million tons.

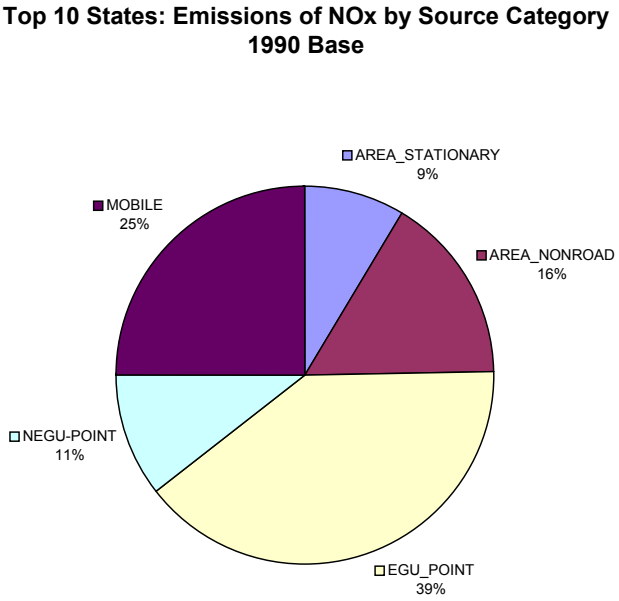
As shown in Figure IV-5 for the top 10 states, mobile plus all point sources accounted for 75% of the NO_x emissions in 1990, with the two largest sectors being EGU point sources (39%) and mobile sources (25%). More of a balance is achieved by Scenario 3, where mobile plus all point sources accounted for just over half of the NO_x emissions (53%). In Scenario 4, roles were reversed and area-stationary plus area-nonroad accounted for over half (58%). In Scenario 4, area-nonroad was the largest NO_x sector at 36%, with area-stationary second at 22%. Mobile was the smallest NO_x sector at 10% and EGU point sources was third at 20%. The shifts and role reversal occurred because major NO_x emissions reductions were projected for both mobile and EGU point sources, 84% and 81%, respectively, with very little reduction in area-stationary NO_x (4%) and area-nonroad (15%) sources.

C. PATTERNS OF AIR POLLUTANT TRANSPORT

1. Source Areas

Long-range transport is involved with each of the pollutants of concern affecting SHEN, especially the pollutants responsible for acidic deposition and visibility degradation, but also for O_3. Sources can have a reach of many hundred kilometers (km) in the prevailing wind direction. The regional reach of these pollutant emissions has been well established by the acid rain programs in North America and Europe (Binkowski et al. 1990, Dennis et al. 1990, Langner and Rodhe 1991, NAPAP 1991, Hov and Hjøllo 1994, U.S. EPA 1995, Wojcik and Chang 1997). The regional reach of O_3 was established in the mid-1990s by the Ozone Transport Assessment Group and further established by the NARSTO O_3 assessment (NARSTO 2000).

(a)



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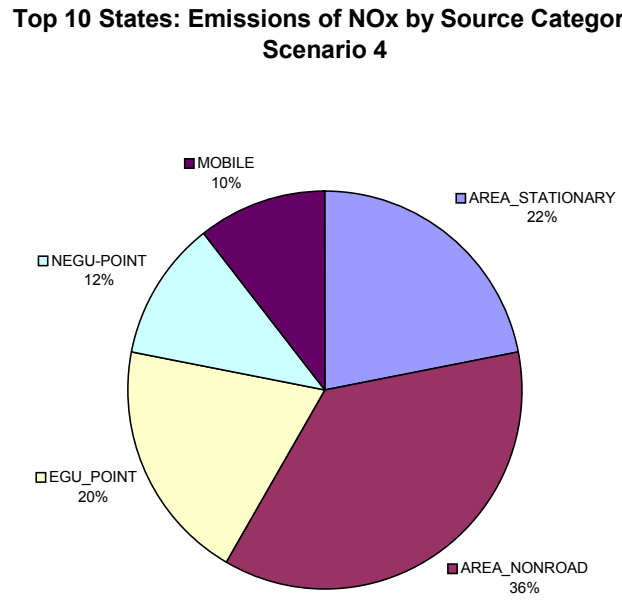

Figure IV-5. Pie chart of NO_x emissions by five-source categories comparing (a) 1990 and (b) Scenario 4.

An extended version of the Regional Acid Deposition Model (RADM; Chang et al. 1987), termed the Extended RADM (Dennis and Mathur 2001), was used to model air pollution transport and deposition in this assessment. The RADM is an Eulerian (fixed-grid) model that was developed under the National Acidic Precipitation Assessment Program as a state-of-the-science model to address regional gas-photochemistry, aqueous chemistry, cloud processes, transport, and wet and dry deposition (Chang et al. 1990). See Section V.D and Appendix C for additional information regarding the model and how it was used for this assessment.

Figure IV-6 shows examples of the reach of emission source subregions responsible for S deposition, oxidized N deposition, reduced N deposition and haze-forming SO_4^{2-} air concentrations, as determined by RADM. The emissions are from a 160x160 km square centered at the joining of the state boundaries of West Virginia, Kentucky and Ohio in the Ohio River Valley. The contour divisions show the distance from the sources to which one must travel to count up one-fourth, one-half, etc. of the total ground-level pollution contributed by the source over the entire eastern North American domain of the model. The deposition loads (kg/ha) or pollutant concentrations ($\mu g/m^3$) along each contour are constrained to have the same magnitude, which sets the shape of the contour. Thus, the shape of the contours about each source subregion shows how the pollutant lifetimes and the climatological mix of wind directions that results in a "prevailing" wind direction combine to produce the overall pattern of pollutant loading or exposure. The contours go farthest away from the source region in the direction of the "prevailing winds" and are closest to the source region in directions "against" the "prevailing" wind.

For all three pollutants, the 25% contour, the area nearest the source with the highest deposition and concentration, is shifted eastward with a tilt to the east-northeast. The 50% contour is further shifted and tilted to the northeast. This is the result of the "prevailing" winds. They tend to transport the pollutant mostly in an arc from the north-northeast to the east. What we see for this particular source subregion in the Ohio River Valley is that the same level of pollution ends up three times farther to the east than to the west. The SO_4^{2-} air concentrations show two main influences: the direction of the "prevailing" winds and the latitudinal variation in the frequency of cloud cover (increasing to the south).

The "reach" of SO_4^{2-} air concentrations, stemming from SO_2, is longest (650-950 km). The reach of NH_3 emissions or reduced N relative to nutrient deposition is the shortest (around 400 km), and the oxides of N and S in terms of acidic deposition have a reach that is in-between

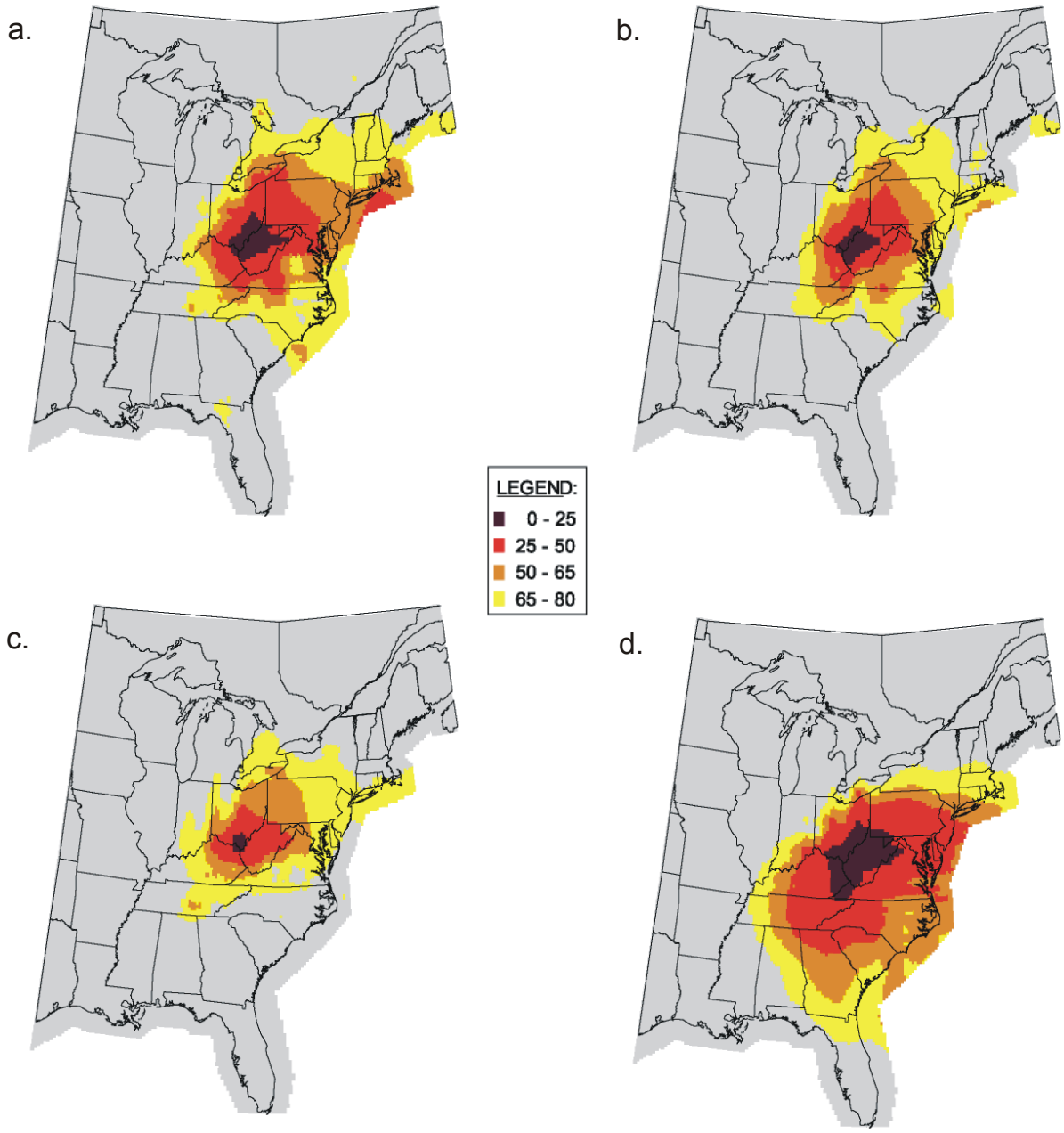

Figure IV-6. Range of influence of (a) sulfur deposition, (b) oxidized nitrogen deposition, (c) reduced nitrogen deposition, (d) sulfate air concentrations expressed as the percent contribution from Subregion 20, a 160x160 km square centered at the joining of the state boundaries of WV, KY, and OH in the Ohio River Valley.

(550-650 km and 600-700 km, respectively). Comparing Figure IV-6(a) with IV-6(d), SO_4^{2-} air concentrations also occur much farther to the southeast, compared to S deposition, because SO_2 is very efficiently converted to SO_4^{2-} in clouds and the frequency of clouds is higher in the south. The effect of clouds influences the shape and apparent "reach" of SO_4^{2-} air concentrations produced from SO_2 emissions from a particular source region.

Hence, we expect pollutants that are emitted within a few hundred km (generally 200 km but up to 300 km for very large sources) of a receptor area (the park) of concern to be very important to the existence of pollution in the receptor area. We also expect pollutants that are emitted within several hundred km still to be important enough to need to consider their responsibility for a portion of the pollution.

We have explored the relative responsibility of regional sources of emissions to air pollution and deposition in SHEN from the perspective of the major airshed contributing pollution to the park. We focused on two main species of emissions: NO_x, responsible for oxidized N deposition (in the form of nitric acid and particulate nitrate), O_3 production, and (beyond scope of this analysis) NO_3^- air concentrations; and SO_2, responsible for S deposition and SO_4^{2-} air concentrations. The geographic pattern of emissions was based on data from the early 1990s, due to the availability of model studies to support this analysis. The airshed view is irrespective of political boundaries and only considers the climatological patterns of transport, transformation and loading/exposure to the end point of interest (the park). We have also explored the relative importance of emissions from several states surrounding SHEN as contributors to the pollution levels in the park. States included were those identified in the airshed analysis as generally being "upwind" of, or in close proximity to, SHEN. Each viewpoint regarding the sources of pollution affecting the park for the 1990 conditions is discussed.

2. Airsheds

Airsheds are more difficult to define than watersheds, because there are no clear boundaries in the atmosphere as there are for surface hydrology. Pollutant concentrations in the atmosphere progressively diminish after they are formed or after they are emitted from a source as they travel downwind, until they become effectively unimportant. The drawing of a major airshed around a geographic region of interest depicts the boundary within which sources of emissions are deemed to contribute substantially to the pollution in the region and outside of which sources

are deemed to play a less important role. The approach used to develop the airsheds for this project was based on analyses presented by Dennis (1997).

The panels in Figure IV-7 show the boundaries (in black) of the major airsheds for SHEN for oxidized N deposition (wet + dry), S deposition (wet + dry) and SO_4^{2-} air concentrations, respectively. The major airsheds are very large compared to the park. As presented in Table IV-5, all three major airsheds of SHEN are approximately a million square kilometers in area. The airsheds for oxidized N and S deposition are the same size and nominally cover 13 states. The airshed for SO_4^{2-} air concentrations is slightly smaller, has a different shape and nominally covers 12 states. The shape of the airsheds is determined by the multi-year climatology of pollutant transport, transformation and loss. The boundary is farthest away from SHEN in the

Table IV-5. Characteristics of major airsheds that contribute air pollution to SHEN.

Oxidized-Nitrogen Deposition Major Airshed	
Size	1,100,800 km^2
States Included	DE, GA, IN, KY, MD, NC, NJ, OH, PA, SC, TN, VA, WV (13 States)
Percent of Deposition Explained by Emissions from within Boundary	85.6%
Percent of Eastern North American Emissions Contained within Boundary	38.9%
Sulfur Deposition Major Airshed	
Size	1,100,800 km^2
States Included	DE, GA, IN, KY, MD, NC, NJ, OH, PA, SC, TN, VA, WV (13 States)
Percent of Deposition Explained by Emissions from within Boundary	83.3%
Percent of Eastern North American Emissions Contained within Boundary	55.8%
Sulfate Air Concentration Major Airshed	
Size	985,600 km^2
States Included	DE, IN, IL, KY, MD, MI, NC, OH, PA, TN, VA, WV (12 States)
Percent of Air Concentration Explained by Emissions from within Boundary	80.4%
Percent of Eastern North American Emissions Contained within Boundary	59.3%

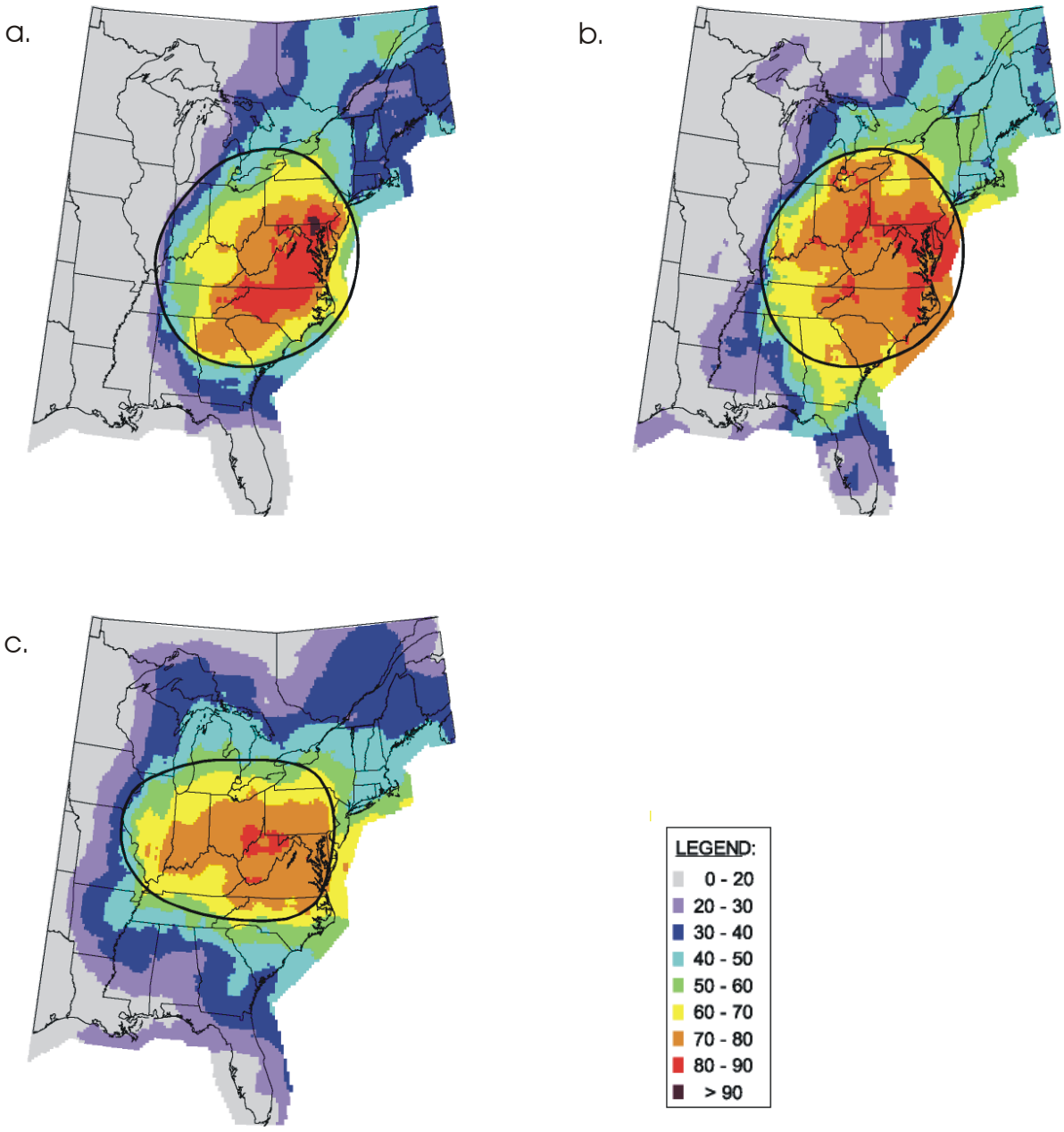

Figure IV-7. Major airsheds for SHEN for (a) oxidized nitrogen deposition, (b) sulfur deposition, (c) sulfate air concentrations. Contours show the percent contribution areas.

direction from which the climatological mix of synoptic meteorological patterns are most conducive to long-range transport in the direction of SHEN (the western or southwestern side). The boundary is closest to SHEN in the direction from which the synoptic patterns are least-conducive to transport towards SHEN (on the eastern side). As noted for Figure IV-7, air pollution travels farthest in the direction of the "prevailing" wind. The SO_4^{2-} airshed boundary does not reach as far to the southeast as does the S deposition airshed because the greater rainfall in the south cleanses the air more of particles while augmenting S deposition.

The contours of percent contribution to deposition or air concentration accounted for by the emissions derived from within the airshed are also depicted in Figure IV-7. SHEN is near to, or in the contour of, the maximum percent explained. This is because the shape of the airshed reflects the climatology of winds bringing pollution to the park from each of the directions, as designed. SHEN is not exactly in the center of the contour of maximum percent explained because the emissions are not distributed uniformly across the airshed. The contours show that the effects of the emissions in terms of deposition or air concentrations tend to continue spreading out well past the airshed boundary in the direction of the "prevailing" wind (to the northeast and out over the ocean). As given in Table IV-5, the percent of oxidized N deposition in SHEN accounted for within the major airshed is 86%. These airshed emissions, on the other hand, represent just 39% of the NO_x emissions of eastern North America. This means that the majority of oxidized N deposition in SHEN (86%) is linked to a relatively small component (39%) of the overall regional emissions. Therefore, NO_x sources within the airshed are very important to N deposition within the park. Similarly, the percentages of S deposition and SO_4^{2-} air concentrations accounted for by SO_2 emissions from within the major airsheds are 83% and 80%, respectively. The SO_2 airshed emissions represent 59% of the eastern North American sulfur oxide (SO_x) emissions.

Table IV-6 gives the emissions of the 15 states nominally covered by any of the airsheds plus one state (New York) included in the analyses of the next section. Because they are included in the SHEN airsheds, these are the states whose emissions have the greatest bearing on the air quality conditions and deposition in SHEN. The emissions of the 13 states included within the S and N deposition airsheds and the 12 states included within the SO_4^{2-} airshed are also summed in the table. Even though the assembly of airshed emissions does not follow state boundaries, the percent of the eastern North American emissions accounted for by the 13-state

Table IV-6. 1990 emissions for the states nominally covered by the SHEN airsheds.

State	SO_2 (tons/yr)	NO_x (tons/yr)	VOC (tons/yr)	CO (tons/yr)
Delaware	100,000	102,989	62,194	269,066
Georgia	1,000,330	687,001	547,448	3,534,801
Illinois	1,261,534	922,261	716,925	3,122,795
Indiana	1,920,416	905,979	541,288	2,301,532
Kentucky	1,034,272	674,772	394,980	1,413,270
Maryland	435,774	354,842	271,811	1,472,063
Michigan	726,298	887,552	868,822	3,481,743
New Jersey	310,629	542,496	540,420	1,841,841
New York	867,415	844,656	996,945	3,892,413
North Carolina	487,616	577,599	673,225	2,755,837
Ohio	2,736,237	1,156,094	849,155	4,138,869
Pennsylvania	1,517,739	1,081,534	827,894	4,180,528
South Carolina	292,567	353,655	369,211	1,598,653
Tennessee	1,077,345	727,134	569,692	2,076,405
Virginia	403,610	564,357	570,977	2,443,994
West Virginia	1,074,715	568,976	200,413	843,463
13-State S&N Deposition Airshed Set	12,391,250	8,297,428	6,418,708	28,870,322
% No. American Emissions	56.3%	40.3%	30.6%	37.5%
12-State SO_4^{2-} Airshed Set	12,775,556	8,524,089	6,547,376	28,499,565
% No. American Emissions	58.1%	41.4%	31.2%	37.1%
Total All 16 States	15,246,497	10,951,897	9,001,400	39,367,273

and 12-state totals given in Table IV-6 are very close to the percentages for the airshed emissions given in Table IV-5.

Not all of the emissions within the airshed contribute equally to the deposition or air concentrations in SHEN. Emissions closer to the park contribute relatively more. Larger emissions sources also contribute relatively more, but proximity is very important. The three airsheds were subdivided into 4 geographic domains, as shown in Figure IV-8. The subdivisions are: local domain, inner domain, middle annulus, and outer annulus. The subdivisions for the oxidized N and S deposition airsheds are comparable. The local domain is the source region that includes SHEN, the receptor region of interest. The inner domain represents the climatologically next most important group of emissions after the local domain in terms of potential importance of emissions affecting SHEN. The inner domain is asymmetric to the west of the park because that is the direction of the influential "prevailing" winds. The middle and outer annuluses

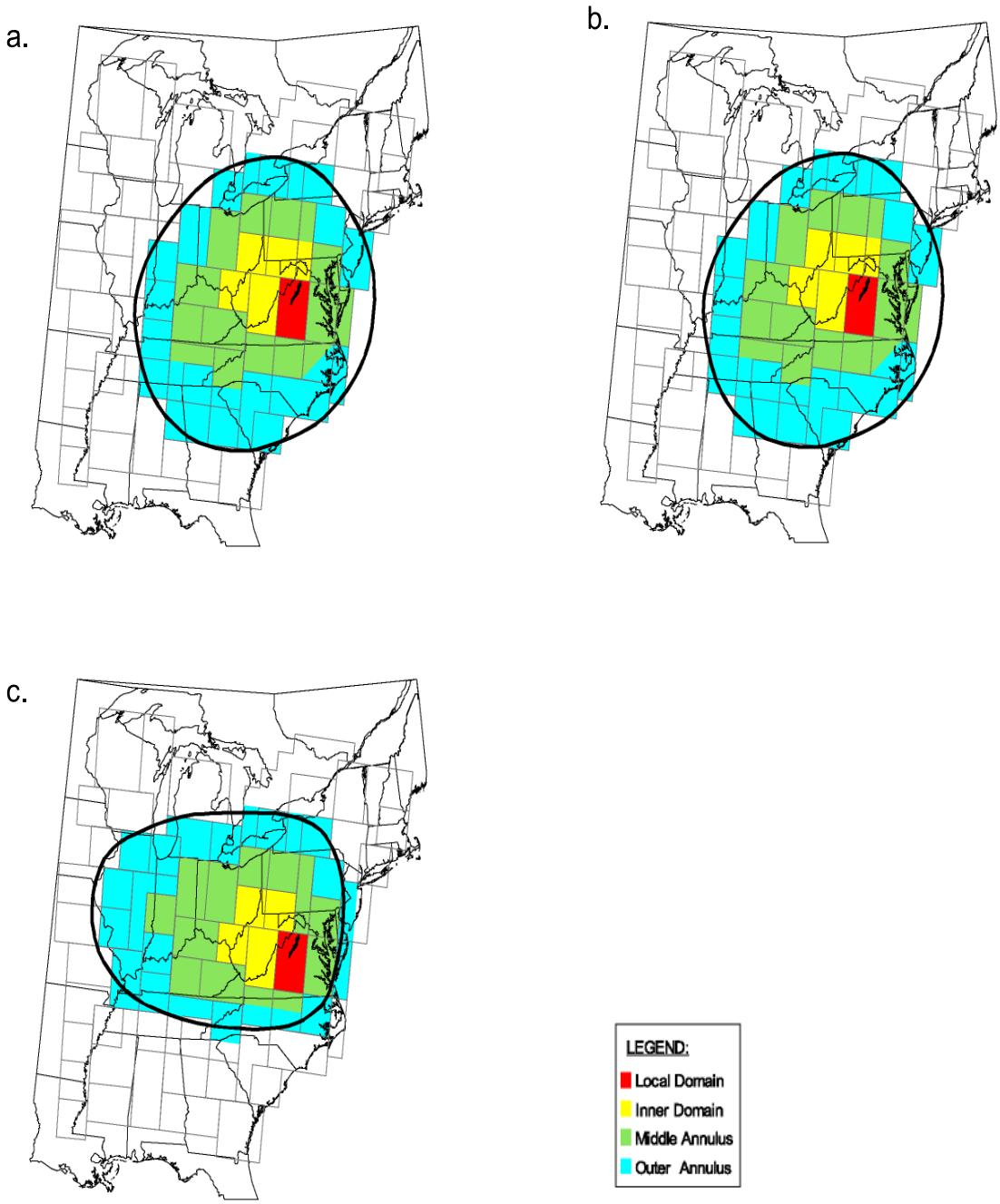

Figure IV-8. Geographic subdivision of the Shenandoah major airsheds: (a) oxidized nitrogen deposition, (b) sulfur deposition, (c) sulfate air concentrations.

subdivide the rest of the airshed in a climatologically consistent manner. The percent of the deposition or air concentrations in SHEN explained by the emissions from each geographic subdivision is given in Table IV-7, along with the percent of eastern North American emissions within each subdivision. The relative efficiency with which a unit of emissions will produce an effect at SHEN is represented by dividing the % Deposition or % Air Concentration number by the % Emissions number. The relative efficiency is given in the last column of Table IV-7.

The effectiveness of the local domain emissions on pollution in SHEN is very high, even though the local emissions are quite low relative to other, more distant emissions sources. The emissions of the next most important geographic subdivision, the Inner Domain, are much less effective at contributing to SHEN's pollution. For deposition, the farther away the geographic subdivision is from the park, the less efficient its emissions are at causing an effect at SHEN.

Table IV-7. Contributions from geographic subdivisions of SHEN major airsheds and efficiency for causing pollution in the park.

Geographic Subdivision	% Deposition/Air Concentration	% Emissions	Efficiency
Local Domain			
Ox-Nitrogen Dep	10.3	0.39	26.4
Sulfur Dep	4.8	0.16	30.0
Sulfate Air Conc.	5.5	0.16	34.4
Inner Domain			
Ox-Nitrogen Dep	26.4	6.3	4.2
Sulfur Dep	34.8	14.4	2.4
Sulfate Air Conc.	25.8	14.3	1.8
Middle Annulus			
Ox-Nitrogen Dep	32.6	13.7	2.4
Sulfur Dep	27.1	17.0	1.6
Sulfate Air Conc.	24.1	17.3	1.4
Outer Annulus			
Ox-Nitrogen Dep	16.3	18.5	0.88
Sulfur Dep	16.6	24.2	0.69
Sulfate Air Conc.	25.0	27.6	0.91
Outside Major Airshed			
Ox-Nitrogen Dep	14.4	61.1	0.24
Sulfur Dep	16.7	44.2	0.38
Sulfate Air Conc.	19.6	40.7	0.48
Efficiency = (%Deposition or %Air Concentration)/(%Emissions)			

From the Inner Domain to the Outer Annulus, the efficiency decreases by factors of 4.8 and 3.5 for oxidized N and S deposition, respectively. For SO_4^{2-} air concentrations, because SO_4^{2-} has a longer lifetime and is produced in transit from SO_2 at an overall moderate rate, the efficiency of emissions for producing SO_4^{2-} particles over SHEN only decreases by a factor of two from the Inner Domain to the Outer Annulus. The in-transit production can replenish some of the SO_4^{2-} lost to dilution, deposition and transport into the upper troposphere. As a result, the percent contributed to SO_4^{2-} at SHEN from the three non-local domains is the same, in contrast to the results found for deposition. As shown in Table IV-8, for the constellation of 1990 emissions, about 60% of the deposition and 50% of the air concentrations in SHEN come from the Inner plus Middle Domains. A clear majority comes from the three innermost domains (including Local).

Table IV-8. Percent of the pollution in SHEN explained by accumulating geographic subdivisions of the major airsheds.

	Oxidized Nitrogen Deposition	Sulfur Deposition	Sulfate Air Concentration
Local	10.3 %	4.8 %	5.5 %
Local + Inner	36.7 %	39.6 %	31.3 %
Inner + Middle	59.0%	61.9%	49.9%
Local + Inner + Middle	69.3 %	66.7 %	55.4 %
Local + Inner + Middle + Outer	85.6 %	83.3 %	80.4 %

In summary, the major airsheds for SHEN are large and they cover many states. Emissions from within the major airsheds account for a large fraction of the pollution in the park. The shape of the airshed is asymmetric to account for the climatology of transport ("prevailing" winds). Not all emissions are equal; local, nearby emissions are exceedingly important and, generally, emissions within about 200 km are much more efficient in producing pollution in SHEN (on a per ton emitted basis) than those from farther away (Table IV-7).

3. Top Five Air Pollutant Source Subregions for SHEN

To provide a sense of the importance of the size of the emissions together with proximity, we labeled the top five source subregions based on the percent of pollution at SHEN explained by each (Figure IV-9). The top five source regions together account for 40%, 46%, and 35% of

the oxidized N deposition, S deposition and SO_4^{2-} air concentrations, respectively. The top 5 source subregions for oxidized N deposition cluster around and include the SHEN local domain, which is labeled number 1 in Figure IV-9. For S deposition, the fact that significant nearby (non-local domain) emissions exist together with very large emissions from sources along the Ohio River Valley determines the top five source subregions. The source subregion centered on the joint intersection of the boundaries of Ohio, West Virginia and Kentucky is number 1. This is the same source subregion presented in Figure IV-6. For SO_4^{2-} air concentrations, local sources and long-range transport from the northwest and west are most important, with the source subregions spreading out to the west. The same source subregion is most important for SO_4^{2-} air concentrations as for S deposition.

4. Relative Contributions by State

Table IV-9 gives the breakdown of relative contributions of emissions to air pollution or deposition within SHEN by state, of the 13 states included in the analysis. The list of states began with the 12 states associated with the SHEN SO_4^{2-} airshed. New York was added because its emissions were large and were roughly similar in distance from SHEN as those from New Jersey. Differences in importance of New York and New Jersey as contributors to air pollution in SHEN highlight the importance of the directional effect of the climatology of transport to SHEN. The states are presented in rank order of contribution for each pollutant. The overall percent explained by the 13 states is consistent with the percent explained by the emissions from within the airsheds. Color contour maps of the percent contribution of the number 1 ranked state are shown in Figures IV-10a, b, and c for S deposition (West Virginia), oxidized N deposition (Virginia) and SO_4^{2-} air concentrations (Ohio), respectively.

The top three states are the same for all three pollutants but the order is different. For S deposition, West Virginia is the top contributor, while for oxidized N deposition Virginia is number one, and for SO_4^{2-} air concentrations Ohio is number one. However, for SO_4^{2-} air concentrations the contribution from the top 3 states are so close as to basically be the same. The top five states are the same for S deposition and SO_4^{2-} air concentrations, with a different order. The top five differ by one state for oxidized N deposition - Kentucky is replaced by North Carolina. In all cases, the top three states account for more than a third of the deposition/air concentrations and the top five states account for more than half. It is interesting

Figure IV-9. Top 5 source regions contributing air pollution in SHEN: (a) oxidized nitrogen deposition, (b) sulfur deposition, (c) sulfate air concentrations. The most important contributing subregion for each constituent is numbered 1, followed systematically by the next 4 most important contributors.

Table IV-9. Percent of the pollution in SHEN explained by state emissions, expressed as the individual state (adjusted) contributions to deposition and atmospheric concentrations (with sulfur nonlinearity adjustment).

State	Sulfur Deposition	State	NO_x Deposition	State	SO_4 Air Concentrations
West Virginia	16.8%	Virginia	14.4%	Ohio	11.9%
Ohio	15.5%	West Virginia	12.3%	Virginia	11.8%
Virginia	10.1%	Ohio	10.9%	West Virginia	11.7%
Pennsylvania	9.9%	Pennsylvania	10.7%	Pennsylvania	10.6%
Kentucky	6.9%	North Carolina	7.8%	Kentucky	7.0%
Tennessee	5.4%	Maryland	7.4%	Indiana	5.8%
Maryland	4.6%	Kentucky	7.0%	Tennessee	5.6%
Indiana	4.4%	Tennessee	4.5%	North Carolina	5.1%
North Carolina	3.8%	Indiana	3.4%	Illinois	3.8%
Illinois	2.9%	Illinois	2.9%	Maryland	3.5%
Michigan	1.1%	Michigan	2.1%	New York	1.7%
New York	0.8%	New York	1.6%	Michigan	1.3%
Delaware	0.4%	Delaware	0.5%	Delaware	0.5%
Top 3 States	**42.4%**	**Top 3 States**	**37.6%**	**Top 3 States**	**35.4%**
Top 5 States	**59.2%**	**Top 5 States**	**56.0%**	**Top 5 States**	**53.0%**
Top 10 States	**80.3%**	**Top 10 States**	**81.2%**	**Top 10 States**	**76.8%**
All States*	**82.6%**	**All States**	**85.4%**	**All States**	**80.3%**

* Includes the 13 states that were part of this analysis

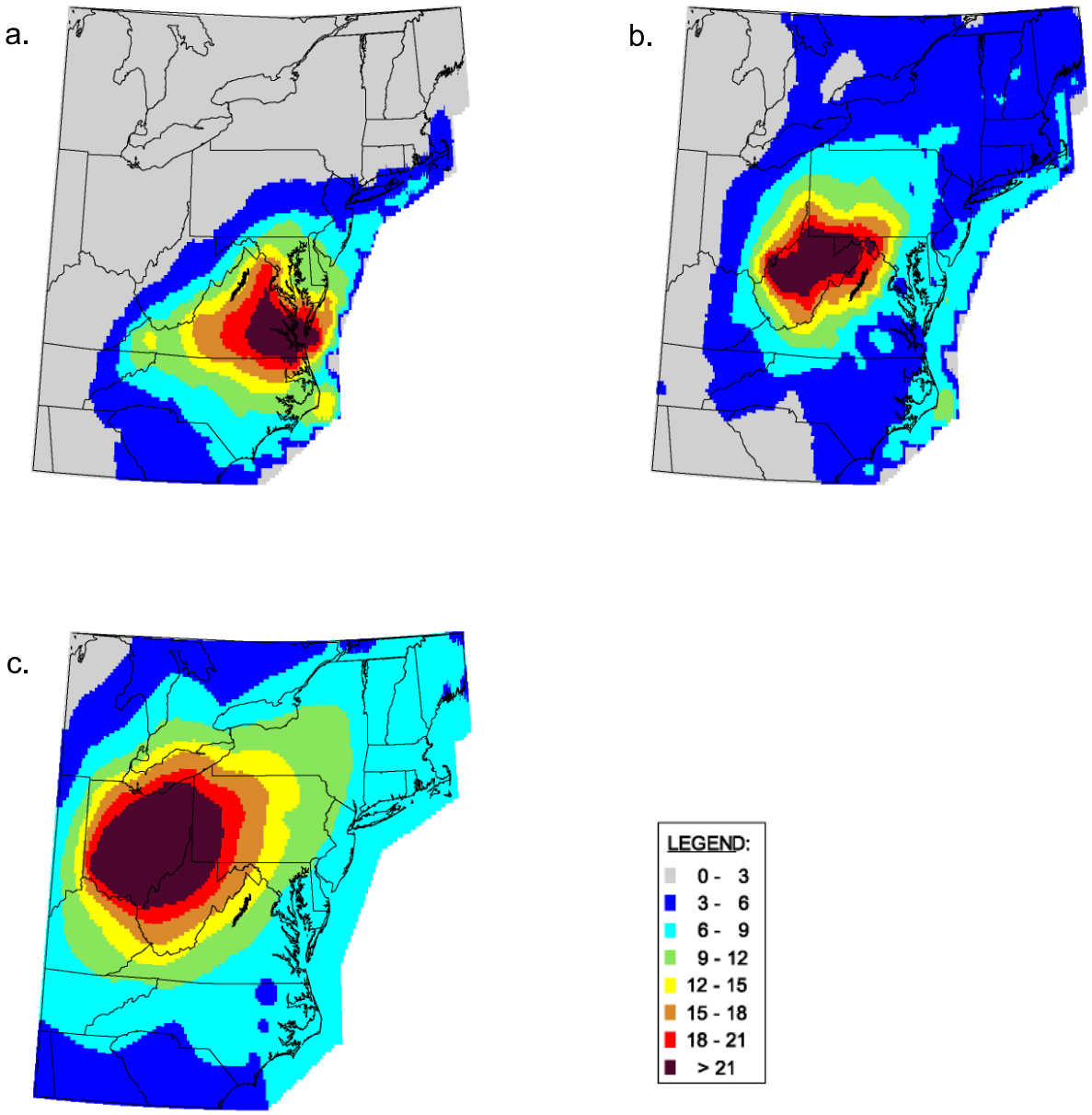

Figure IV-10. First-ranked state percent contribution contour for (a) oxidized nitrogen deposition (VA), (b) sulfur deposition (WV), (c) sulfate air concentrations (OH).

to note that while New York has a fair amount of emissions, it ranks well down on the list of contributing states, even lower than Illinois which is much farther away, because New York is located in a direction opposite the "prevailing" winds for SHEN.

D. IN-PARK EMISSIONS

An air emissions inventory was completed for SHEN by the NPS ARD in July, 2002. Table IV-10 provides a summary of in-park emissions. Prescribed burning, fireplaces and campfires, and mobile sources are the largest contributors to air pollutant emissions in SHEN. Stationary sources contribute very little to the overall park emissions.

The park is surrounded by the counties of Albermarle, Augusta, Greene, Page, Madison, Rappahannock, Rockingham, and Warren. Emission estimates for these counties, and for the Commonwealth of Virginia, were obtained by the NPS ARD from the 1999 National Emissions Inventory (NEI) maintained by the U.S. EPA. It is important to note that differences may exist between the methodologies used to generate the park emissions inventory and those stationary sources, whereas the NEI treats them as area sources. Table IV-11 provides a comparison among SHEN emissions and those from surrounding counties and the state. For all pollutants, SHEN emissions account for less than 1% of the surrounding county emissions. Figure IV-11 displays the contribution of in-park emissions relative to the surrounding counties.

Table IV-10. SHEN 1999 emissions (tons) summary. (Source: Aaron Worstell, NPS Denver)

	VOC	NO_x	SO_2	PM_{10}	CO
Stationary Sources					
Generators	0.1	0.6	0.0	0.0	0.8
External Combustion	0.0	0.0	0.0	0.0	0.0
Wastewater Treatment Plants	0.1	–	–	–	–
Gasoline Tanks	0.5	–	–	–	–
Subtotal	0.7	0.6	0.0	0.0	0.8
Mobile Sources					
All Vehicles	32.8	31.3	–	40.8	343.5
Area Sources					
Prescribed Burning	41.4	25.8	–	77.5	723.7
Fireplaces and Campfires	62.4	0.7	0.1	9.4	68.8
Subtotal	103.8	26.6	0.1	87.0	792.6
OVERALL TOTAL	137.3	58.4	0.1	127.8	1136.9

Table IV-11. Annual emissions totals (tons) from within SHEN and comparison with surrounding counties. (Source: Aaron Worstell, NPS Air Resources Division, Denver)

	VOC	NOx	SO_2	PM_{10}	CO
Area and Mobile Source					
SHEN	136.6	57.8	0.1	127.8	1136.0
Albermarle Co.	6655.0	8035.0	591.0	6005.0	47313.0
Augusta Co.	6248.0	6943.0	462.0	6512.0	36487.0
Greene Co.	906.0	812.0	62.0	1450.0	5128.0
Madison Co.	1100.0	944.0	70.0	1788.0	5733.0
Page Co.	1570.0	1568.0	112.0	2086.0	9974.0
Rappahannock Co.	562.0	490.0	36.0	989.0	2661.0
Rockingham Co.	5640.0	7214.0	488.0	7286.0	31925.0
Warren Co.	2232.0	2550.0	166.0	1930.0	15440.0
Surrounding County Total	24913.0	28556.0	1987.0	28046.0	154661.0
VA State Total	437462.0	406884.0	40106.0	344603.0	2452333.0
Point Source					
SHEN	0.7	0.6	0.0	0.0	0.8
Albermarle Co.	167.0	289.0	563.0	96.0	121.0
Augusta Co.	379.0	1067.0	1732.0	156.0	78.0
Greene Co.	13.0	20.0	0.5	2.0	17.0
Madison Co.	14.0	3.0	13.0	1.0	1.0
Page Co.	44.0	41.0	19.0	4.0	11.0
Rappahannock Co.	0.5	1.0	1.0	1.0	1.0
Rockingham Co.	633.0	568.0	1073.0	196.0	205.0
Warren Co.	57.0	39.0	109.0	18.0	4.0
Surrounding County Total	1307.5	2028.0	3510.5	474.0	438.0
VA State Total	59144.0	168416.0	334941.0	19550.0	66873.0
All Sources					
SHEN	137.3	58.4	0.1	127.8	1136.9
Albermarle Co.	6822.0	8324.0	1154.0	6101.0	47434.0
Augusta Co.	6627.0	8010.0	2194.0	6668.0	36565.0
Greene Co.	919.0	832.0	62.5	1452.0	5145.0
Madison Co.	1114.0	947.0	83.0	1789.0	5734.0
Page Co.	1614.0	1609.0	131.0	2090.0	9985.0
Rappahannock Co.	562.5	491.0	37.0	990.0	2662.0
Rockingham Co.	6273.0	7782.0	1561.0	7482.0	32130.0
Warren Co.	2289.0	2589.0	275.0	1948.0	15444.0
Surrounding County Total	26220.5	30584.0	5497.5	28520.0	155099.0
VA State Total	496606.0	575300.0	375047.0	364153.0	2519206.0

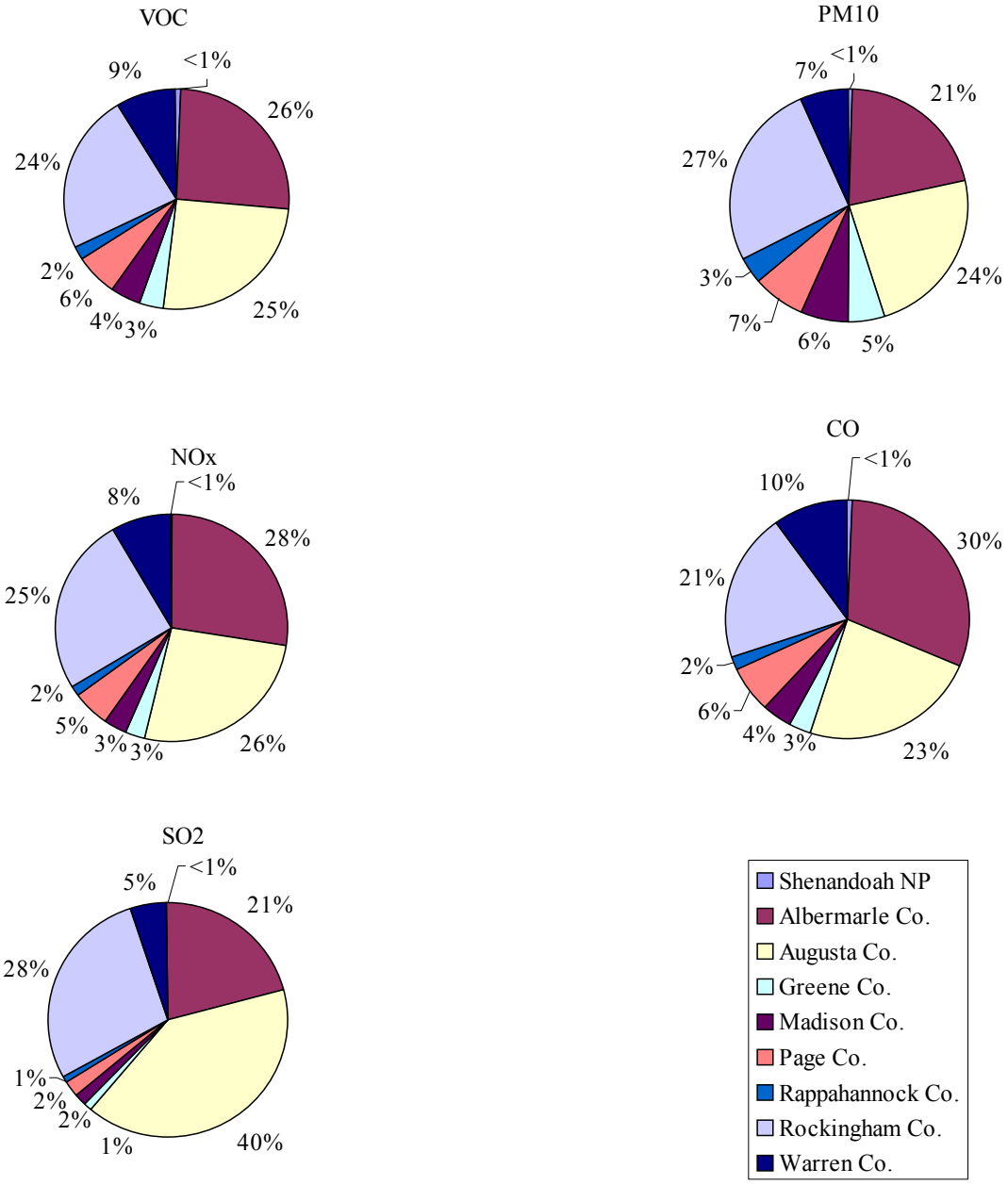

Figure IV-11. In-park SHEN emissions relative to emissions from surrounding counties. (Source: Aaron Worstell, NPS Air Resources Division, Denver)